PHYS 393
Low Temperature Physics
Set 5:

Liquid He^4-He^3 mixtures

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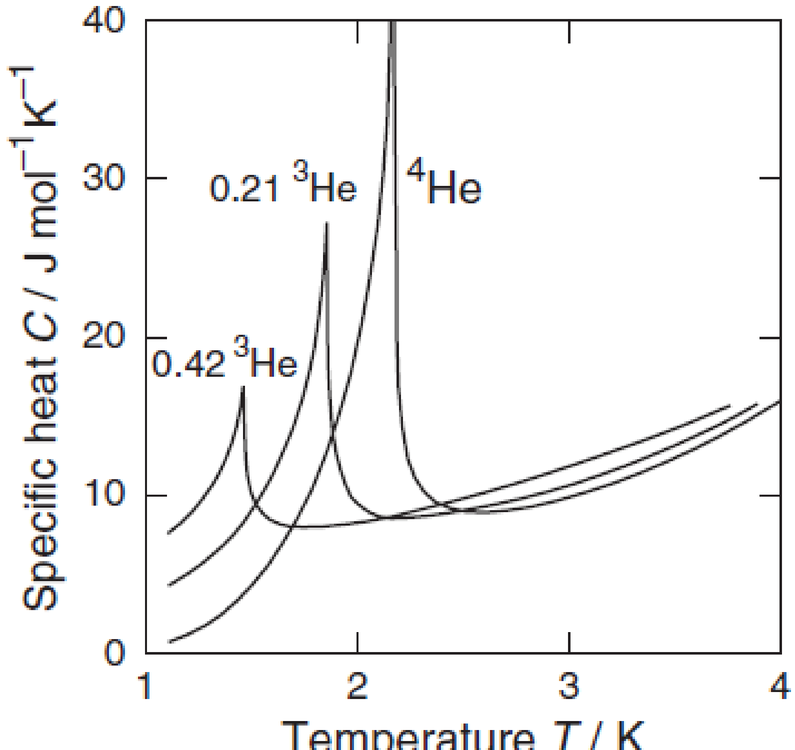
He^3-He^4 liquid mixtures

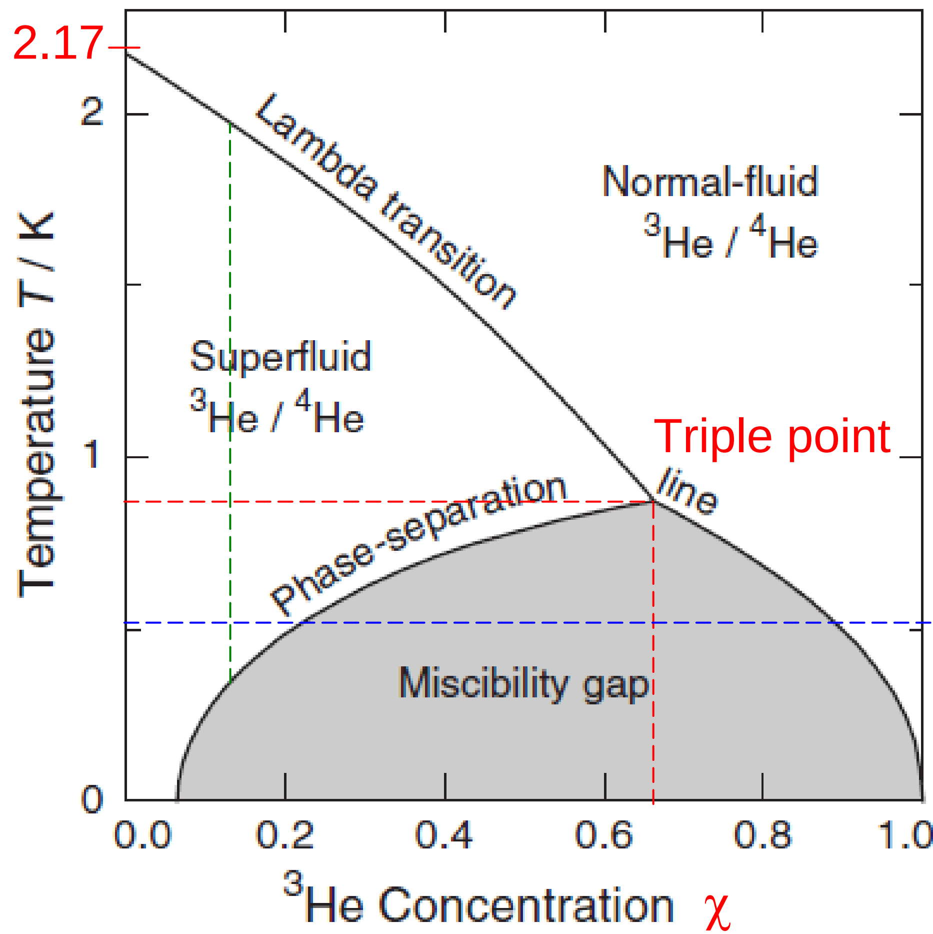
- Significant influence of He^3 impurities on He^4 hydrodynamics and superfluidity transition (1950s)
- Technical importance: He^3 –He^4 mixtures used in dilution refrigerators to achieve very low temperatures (down to 5mK)
- Theoretical interest : near-perfect Fermi gas
- He^3 concentration $\chi = N_3/(N_3+N_4)$, where N_3 and N_4 are the quantities of H^3, He^4



Specific heat (heat capacity) of liquid Helium mixtures as function of He^3 content (pure He^4 also shown)

Liquid He^3-He^4 phase diagram

- Above 0.87K: transition between normal and superfluid
- Increasing χ lowers transition temperature
- Miscibility gap below 0.87K: no homogeneous mixture; two liquids (grey region in graph)
- He^3-rich liquid floats above He^4-rich liquid (denser)



Two phase region (miscibility gap)

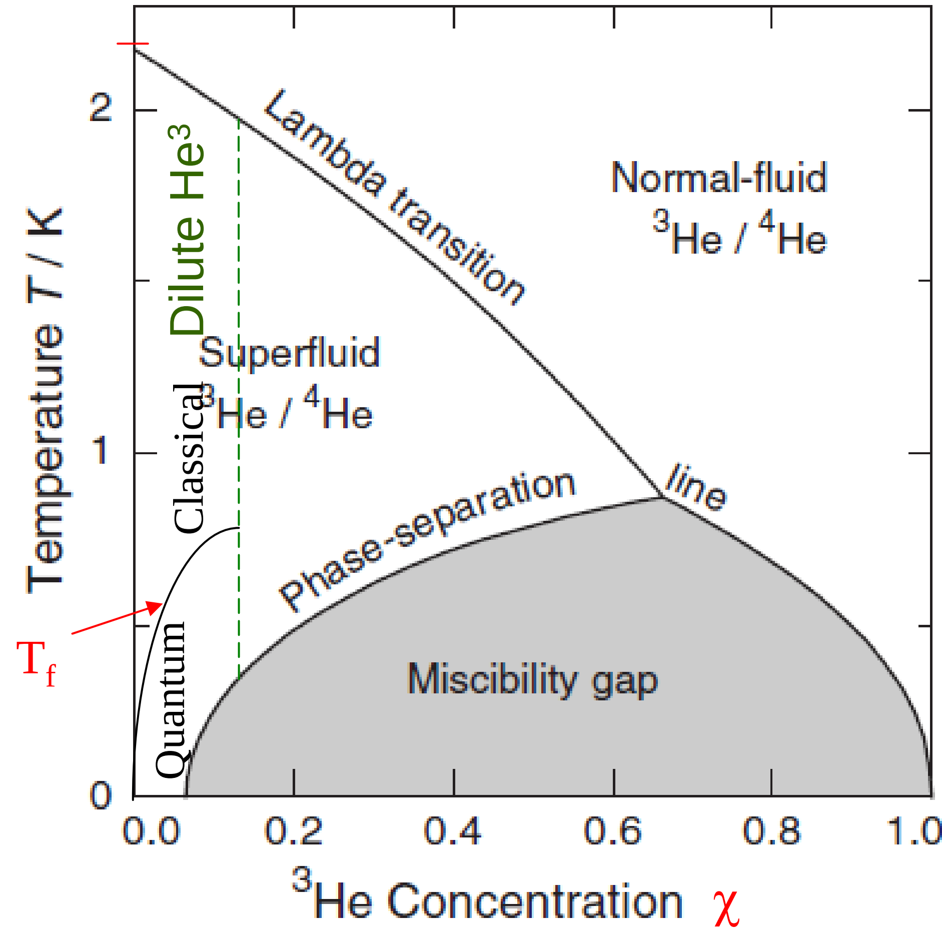
- He^3-rich component (on right part of phase-separation line) has He^3 content between 67% (triple point) and 100% at T=0

- He^4-rich component (on left part of phase-separation line) has He^3 content between 67% (triple point) and 6% at T=0

- Finite He^3 solubility at T=0: Both isotopes have the same Van der Waals potentials, but He^3 atoms are lighter hence have larger zero-point motion
  - He^3 atom is closer to He^4 atoms than other He^3 atoms
  - He^3-He^4 bonding is stronger than He^3-He^3

Dilute He^3-He^4 II liquid mixtures

- In region $\chi<0.15$ as T decreases He^3 atoms are separated by increasing proportion of superfluid He^4 (Landau two-fluid theory)
- Creates system of weakly interacting fermions in a sea of He^4 bosons
- At small concentrations He^3 atoms can be described as a free gas in a massive vacuum
- He^3 atoms must displace He^4 atoms as they move
- Described as effective mass $m_3^*=2.4m_3$



Dilute mixtures

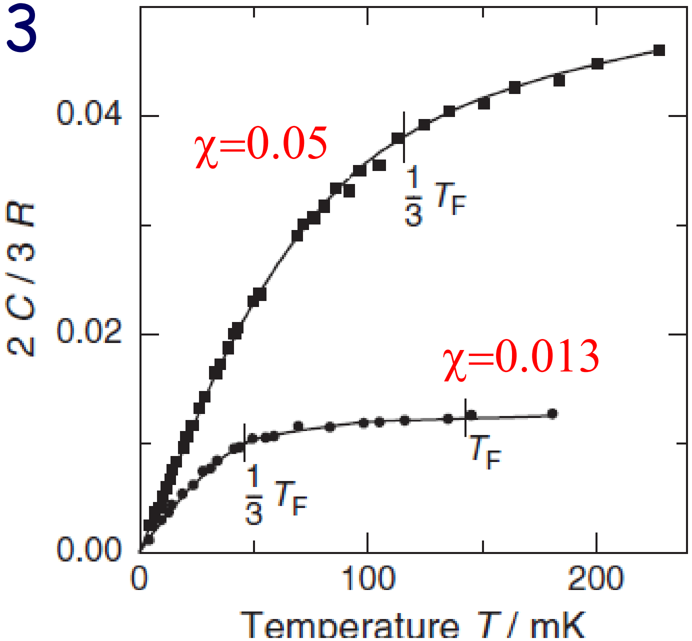
Fermi temperature given by $$T_f = \frac{\hbar^2}{2m_3^* k}\left(3\pi^2 \frac{N_3}{V}\right)^{2/3}$$

N_3/V: density of He^3 atoms, can be used to adjust T_f

- $T < T_f$: Fermi gas in quantum state $$C_V = \gamma T$$
- $T > T_f$: Fermi gas in classical state $$C_V = \frac{3}{2} Nk$$

Transition around $T_f /3$

Excellent agreement with Fermi gas theory



He^3 in mixture

- Flow experiments demonstrate that He^3 atoms in He^3/He^4 II move with normal component of He^4 – do not participate in superfluid viscosity-free flow

- Attempts ongoing since many years to observe superfluid transition of He^3 in mixture
- Not easy to predict transition temperature
- Not observed yet